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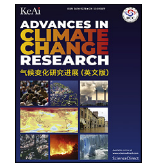

The half-degree matters for heat-related health impacts under the 1.5 °C and 2 °C warming scenarios: Evidence from ambulance data in Shenzhen, China

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Abstract

The Paris Agreement has prompted much interest in the societal and health impacts of limiting global warming to 1.5 °C and 2 °C. Previous assessments of differential impacts of two targets indicate that 1.5 °C warming target would substantially reduce the impact on human health compared to 2 °C, but they mainly focused on the magnitude of temperature changes under future climate change scenarios without any consideration of greater frequency of cumulative heat exposures within a day. Here we quantified the health risks of compound daytime and nighttime hot extremes using morbidity data in a megacity of China, and also identified the time-period of heat exposure with higher risks. Then we projected future morbidity burden attributable to compound hot extremes due to the half-degree warming. We estimated that the 2 °C warming scenario by 2100 as opposed to 1.5 °C would increase annual heat-related ambulance dispatches by 31% in Shenzhen city. Substantial additional impacts were associated with occurrence of consecutive hot days and nights, with ambulance dispatches increased by 82%. Our results suggested that compound hot extremes should be considered in assessment of heat-related health impacts, particularly in the context of climate change. Minimizing the warming of climate in a more ambitious target can significantly reduce the health damage.

Keywords: Climate change; Compound hot extreme; Paris agreement; Human health; Morbidity effect

1. Introduction

Increases in average temperature caused by climate change is expected to lead to longer, more severe and frequent heat events, known as heat waves (Perkins and Lewis, 2020; Guo et al., 2017). Daily minimum temperature was found to have

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increased faster than daily maximum or mean temperature, contributing to more frequent occurrence of nighttime heat events (Ho et al., 2017). Heat events have changed from daytime hot extremes into nighttime hot extremes, and consecutive daytime and nighttime heat events (hereafter referred to as compound hot extremes) since the 1980s (Ma and Yuan 2021; Ullah et al., 2019). In particular, with the rapid process of urbanization, the urban heat island effect can further increase the frequency of nighttime hot extremes around cities, resulting in high temperatures lasting for a whole day (Ren et al., 2021).

Extreme heat events are the most prominent cause of weather-related health risks around the world (Huang et al., 2012; Macintyre et al., 2018; Wang et al., 2019). Epidemiological studies have shown that nighttime hot extremes may cause more severe health impacts when compared with daytime hot extremes or heat events defined by daily mean temperatures (Lan et al., 2014; Murage et al., 2017; Obradovich et al., 2017; Sariyer et al., 2017). Due to the global warming, the population exposure to compound hot extremes has increased markedly in recent years (Wang et al., 2020b; Zhang et al., 2020). However, most health risk assessments still used a single temperature index (i.e. daily maximum/mean/minimum temperature) to reflect the heat exposure throughout the day (Armstrong et al., 2017; Ban et al., 2017; Chen et al., 2017; Guo et al., 2017). This has led to less attention being paid to the health risks of continuous exposure to high temperatures during the day and at night.

To date, projected heat-related health risks have been well-established under the Representative Concentration Pathways (RCPs) (Gasparrini et al., 2017; Huang et al., 2011; Lee et al., 2020). Previous studies have consistently projected that future heat-related deaths will be significantly aggravated under high emission scenarios (RCP8.5 and RCP4.5) (Yang et al., 2021). Even when under low emission scenario (RCP2.6), warming climate and heat events will still cause a large number of heat-related health impacts (Lee et al., 2020). To combat the impacts of climate change, the Paris Agreement set the goals of limiting global warming to well-below 2 °C and preferably to 1.5 °C, which putting forward more stringent requirements of GHG emissions.

Multiple lines of new evidences indicate that compound hot extremes are predicted to occur more frequently in the 2 °C warming scenario than that in 1.5 °C (Chen et al., 2019; Mukherjee and Mishra 2018; Wang et al., 2020a). However, previous studies assessing future heat-related health impacts under 1.5 °C and 2 °C warming scenarios only considered changes in frequency or intensity of heat events (Ebi et al., 2018; Gasparrini et al., 2017; Hajat et al., 2014; Huang et al., 2011; Kim et al., 2016; Kingsley et al., 2016). Neglecting changes of heat characteristics in cumulative exposure within a day may underestimate future health impacts of heat events.

Shenzhen is one of the largest cities in China and home to around 11.9 million residents with a population density of 9322 persons km^{-2} in 2016 (SSB 2017). As a subtropical megacity developed as an economic zone from late 1970s, Shenzhen may represent the scenarios of both metropolitans (e.g., Beijing, Shanghai, Guangzhou) and rapidly developing cities (e.g., Wuhan, Chongqing, Hangzhou) in China due to the similar characteristics of urban agglomeration. A typical subtropical monsoon climate prevails in Shenzhen, with wet, hot and long-lasting summers. These demographic and climatic characteristics make Shenzhen a perfect sample for investigating the impacts of ambient heat. To assess the health impacts of consecutive heat exposure during a day under the 1.5 °C and 2 °C warming scenarios, we assess the health risks due to consecutive daytime and nighttime heat exposures using the morbidity data in Shenzhen, China. And then quantify heat-related health burdens in the 1.5 °C and 2 °C warming scenarios with the consideration of changes in compound hot extremes, so as to further determine the extent of additional health risks of climate change from 1.5 °C to 2 °C warming level and provide a more reliable projection of heat-related health impacts.

2. Methods

2.1. Morbidity data

Emergency ambulance dispatches, the front-line of medical services, usually relate to acute health outcomes. The number of dispatches is considered indicative of the extent of people affected by hazardous weather, and is therefore selected as the health outcome of interest in this study. Furthermore, this indicator also delivers a more accurate picture of the occurrence time of heat-related diseases compared to either mortality data or hospital admissions.

Daily records of emergency ambulance dispatches from January 1st, 2015 to December 31st, 2016 were obtained from the Shenzhen Medical Information Center which collects ambulance dispatch information for the whole city. The cause of ambulance dispatches is classified based on doctor diagnoses and/or symptoms. Ambulance dispatches are also grouped by gender and age categories (≤17, 18−44, 45−59, and ≥60 years old).

2.2. Climate data

Daily observations of maximum and minimum temperatures, and relative humidity during 2015−2016 were obtained from the China Meteorological Data Sharing Service System. The National Weather Station in Shenzhen is located in Futian District, the central area of Shenzhen.

Daily mean air quality data during 2015−2016 was obtained from the National Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035/), which was released by the China National Environmental Monitoring Center, and computed from 13 state-controlled monitoring sites across Shenzhen representing the average air pollutants levels in city. Since the air pollutants (such as $PM_{2.5}$, O_3, and SO_2) could modify the effects of temperature on human mortality or morbidity risks, in line with previous temperature-related health risk assessments (Gasparrini et al., 2015; Patel et al., 2019; Wang et al., 2020; Weinberger et al., 2017; Yang et al., 2021), we controlled the particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), ozone (O_3), and sulfur dioxide (SO_2) in the DLNM model.

We focus on summer months from May to October when temperatures are at their highest. To assess whether impacts of hot extremes vary across the summer season, summer was divided into early summer (May−June), mid-summer (July−August), and late summer (September−October).

A hot event was defined as daily maximum or minimum temperature higher than its 90th percentile for the specific calendar day during May to October, which is in line with previous literature (Huang et al., 2018; Xu et al., 2019; Yin et al., 2018). Event types were further specified by the timing of event occurrence, as a) compound hot extreme—consecutive occurrence of a hot day and a hot night within 24 h (a day that daily maximum and minimum temperature are higher than the 90th percentile for the temperature ranges); b) daytime hot extreme—a hot day without a following hot night (a day that daily maximum temperature is higher than the 90th percentile only); and c) nighttime hot extreme—a hot night without a preceding hot day (a day that daily minimum temperature is higher than 90th percentile). There was no overlap amongst the three types of hot extremes.

The projected daily maximum and minimum temperatures were derived from the 11 members of Community Earth System Model (CESM), which provides a set of fully coupled simulations running from 1850 to 2100 with a horizontal resolution of about 1° × 1° (Sanderson et al., 2017). These CESM simulations are specifically developed for a future characterized by stabilized 1.5 °C and 2 °C warming worlds by the end of the 21st century (2071−2100), in accordance with the Paris Agreement. We used the grid centered at 114°E, 23°N to represent Shenzhen, with other neighboring grids with 1−2 grid distances also examined in sensitivity tests. Temperatures in the used grid show good consistency with observed temperatures in Shenzhen, and so using neighboring stations would not change our conclusions in any significant manner. We used the 11-member ensemble mean number of events to represent anthropogenically-forced evolutions of hot extremes in the future, thus better informing 'avoided heat-related risks' owing to curbing emissions of greenhouse gases.

2.3. Modeling of exposure−response relationships

A time-series quasi-Poisson regression analysis was used to estimate the effects of hot extremes on daily ambulance dispatches. A distributed lag non-linear model (DLNM) was used to examine the non-linear and delayed effects of temperature (Gasparrini et al., 2010). A binary hot extreme variable (0 or 1) was used for each day. Hot extreme days were categorized as 1 while a normal day was categorized as 0. Separate models were used to estimate risks of heat-related ambulance dispatches for each type of hot extremes. The cumulative lagged effect of 0−1 d was chosen to present the estimates, as suggested by previous research which found that heat effects on ambulance dispatches diminished within one day (Guo 2017). Time-varying confounders and known predictors of ambulance dispatches were controlled in the model; these were relative humidity, air pollutants, day of the week, long-term trend and seasonality. Sensitive analysis was conducted to merge the three types of compound events into the same DLNM model trough a dummy variable. A nature cubic spline with 6 degrees of freedom per year was used in the model to control the seasonality and long-term trends. Daily mean relative humidity, as potential confounding variables, was modeled as a natural cubic spline (ns) with 3 degrees of freedom.

2.4. Ambulance dispatches attributable to future hot extremes

To calculate ambulance dispatches attributable to hot extremes, we first calculated the attributable fraction (AF) of daily ambulance dispatches for each hot extreme (daytime, nighttime and compound event) using relative risks (RR) in the baseline model (Eq. 1). HEi is the type of hot extreme, and i refers to the types of hot extremes (daytime, nighttime and compound).

$$AF(HE_i) = [RR(HE_i) - 1] / RR(HE_i) \tag{1}$$

Ambulance dispatch numbers attributable to each hot extreme per year (AN) for the years 2020−2099 in the 1.5 °C and 2 °C warming scenarios was then estimated (Eqs. 2 and 3). Mean observed ambulance dispatch count (MDC) was calculated as the total number of ambulance dispatches occurred during each hot extreme for the period 2015−2016. ND is the number of days identified as hot extreme (simulated).

$$AN = \sum [AF(HE_i) \times MDC_i \times ND(HE_i)] \tag{2}$$

$$MDC_i = \frac{(Total\ ambulance\ dispatch\ during\ event)_i}{(Total\ number\ of\ event\ during\ 2015-2016)_i} \tag{3}$$

To focus on future changes in hot extremes and the health risks its poses, we assumed that there will be no changes in demography, health service demand, and heat adaptation of the population, which was in line with previous studies (Benmarhnia et al., 2014; Vicedo-Cabrera et al., 2018; Wang et al., 2016a). This ensures that the changes in projected ambulance dispatches are exclusively temperature-driven.

To determine whether cumulative exposure to heat produced additional health effects, we assessed the difference in heat-related ambulance dispatches with and without the consideration of cumulative exposure. We further estimated health impacts due to changes in thermal characteristics (timing of hot extremes) from 1.5 °C to 2 °C warming scenarios. Specifically, we projected the number of ambulance dispatches attributable to hot extremes defined by a single temperature criterion (if daily maximum temperature is above the 90th percentile of the temperature range), and then compared it with the bivariate-based (i.e. T_{max} and T_{min}) compound hot extremes.

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R software was used to perform all analyses (version 3.5.3, http://www.R-project.org/), with 'dlnm' package to create the DLNM model.

3. Results

During May to October in the years 2015−2016, a total of 176,319 ambulance dispatches were recorded in Shenzhen, of which 51% were for people aged 18−44 years. The leading reasons for calling ambulance services were trauma (35%), cardiovascular disease (CVD) (10%) and mental and behavior disorders (10%) (Table 1). Ambulance service demands were the highest in early summer (Table A1).

Threshold of daytime hot extremes was identified as 33.9 °C in daily maximum temperature, and threshold of nighttime hot extremes was identified as 27.9 °C in daily minimum temperature. There were 12 daytime heat events, 11 nighttime heat events and 7.5 compound heat events identified per year in Shenzhen. The distribution of compound events revealed that the occurrence of nighttime hot extremes was generally earlier than that of daytime hot extremes. The nighttime hot extremes mostly occurred in early summer, while the daytime hot extremes usually occurred in mid-summer. This coincides with a greater demand for ambulance services during early summer in Shenzhen (Fig. 1). In comparison, daytime events represented the majority of hot extremes during mid-summer. Additionally, an increase in daily ambulance dispatches was observed during the identified hot extremes.

Relative risks (RR) and 95% confidence intervals (CI) were calculated to determine the risk, or likelihood, of an ambulance dispatch on hot extreme days compared to non-hot extreme days during May−October. The risk of ambulance dispatches was the highest during the compound hot extreme (RR = 1.084, 95% CI: 1.032−1.138), followed closely by nighttime events (RR = 1.080, 95% CI: 1.040−1.121) (Fig. 2). Sensitive analysis shows that, compared with separate DLNM models, utilizing one DLNM model with a dummy variable to represent three types of hot extremes would present similar heat-related risks of heat-related ambulance dispatches. And better model fitness was found in the separate DLNM models (Table A2).

In early summer, compound hot extremes were identified as a major source of health risk (RR = 1.20, 95% CI: 1.03−1.40), while during mid-summer, higher risks were found during daytime events (RR = 1.06, 95% CI: 1.00−1.12). In late summer, both daytime and nighttime hot extremes are associated with high, though not significant, risks of ambulance dispatches (RRs were 1.22 [0.82, 1.80] and 1.26 [0.87, 1.82], respectively).

Furthermore, we observed various population characteristics that modified the risk of ambulance service demands (Fig. 3). Specifically, males and working-age population (aged 18−44 and aged 45−59) were found to have higher risk of heat-related ambulance dispatches during the compound events. Additionally, males and older working adults also had higher risks associated with ambulance dispatches during the nighttime events. By contrast, adults aged greater than 60 were at higher risk during daytime hot extremes. Furthermore, heat-related ambulance service demand was not particularly modified by the medical reason for the call, except for urinary disease and alcohol intoxication during the component events and trauma during the nighttime events.

Based on the above results, we projected the number of hot extremes in the future based on both 1.5 °C and 2 °C warming scenarios. If a 2 °C warmer world is achieved rather than a

Table 1
Descriptive statistics of ambulance dispatches during warm seasons in Shenzhen, China in 2015−2016.

Group		Total dispatches	Daily average dispatches	Percentage (%)
All		176,319	478 [359, 667]	–
Gender	Male	92,066	250 [186, 383]	52.2
	Female	53,856	146 [101, 207]	30.5
	Not known	30,397	82 [47, 141]	17.2
Age (years)	0−17	9556	25 [12, 45]	5.4
	18−44	90,063	242 [181, 367]	51.1
	45−59	25,072	67 [41, 102]	14.2
	≥60	21,037	57 [32, 79]	11.9
Diagnosis	Trauma	60,962	164 [114, 276]	34.6
	Cardiovascular disease	18,323	50 [30, 70]	10.4
	Mental and behavior disorder	17,586	47 [30, 72]	10.0
	Alcohol intoxication	16,292	42 [15, 115]	9.2
	Dizziness	16,062	43 [19, 74]	9.1
	Gastrointestinal disease	10,344	28 [14, 48]	5.9
	Traffic accident	8125	22 [7, 43]	4.6
	Respiratory disease	7318	19 [9, 67]	4.2
	Obstetric or gynecological problem	6462	17 [7, 35]	3.7
	Urinary disease	4159	11 [4, 22]	2.4
	Unclassifiable or not known	41,766	113 [74, 189]	23.7

Note: A patient may be diagnosed with more than one disease. Total diagnoses count (207, 399) therefore is greater than the number of patients (176, 319).

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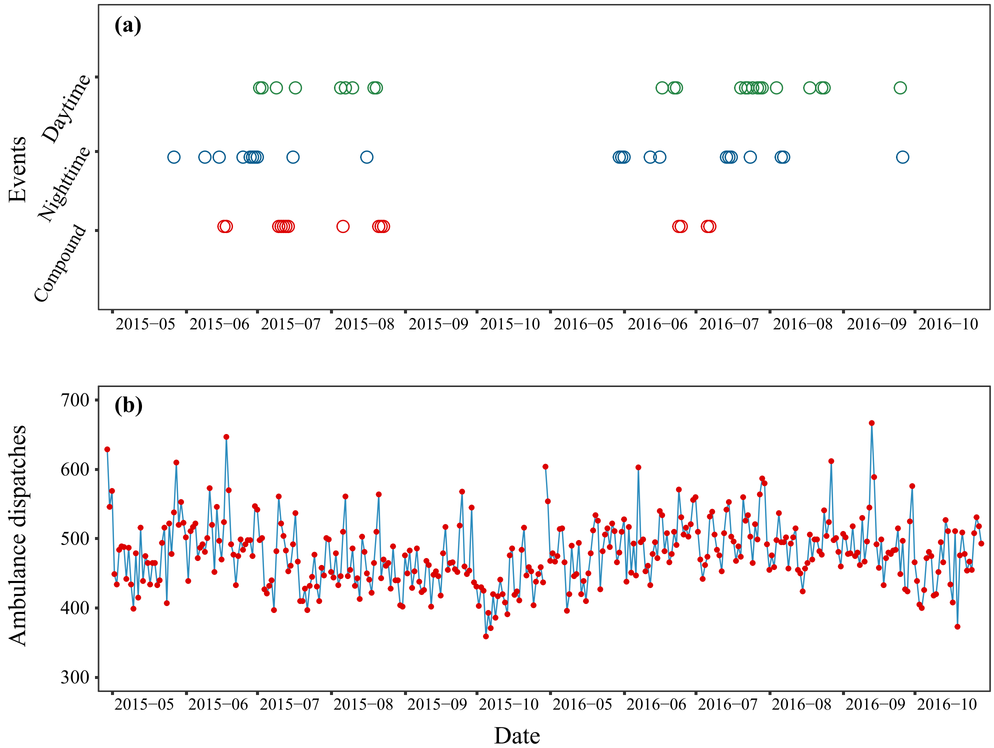

Fig. 1. Number of hot extremes (a) and daily ambulance dispatches (b) in Shenzhen, China during warm seasons in 2015−2016 (A circle represents a compound event. The green circles reflect daytime hot extremes, blue circles represent nighttime hot extremes, and the red for compound hot extremes. The red dot in the bottom panel shows the daily number of ambulance dispatches).

1.5 °C world, it is predicted that there will be considerably more hot extreme days as well as compound hot extremes (Fig. 4). Compared to the 1.5 °C warming scenario, a 2 °C warming would increase the number of total hot extremes by 12% (67 d per decade) during 2020−2059, and by 20% (124 d per decade) during 2060−2099. During the 2020s, in a 2 °C warming scenario, nighttime events will account for 56% of total hot extremes, and compound events for 18%. By the 2090s, compound events will increase to 42% of all hot extremes, and nighttime events will contribute 41%.

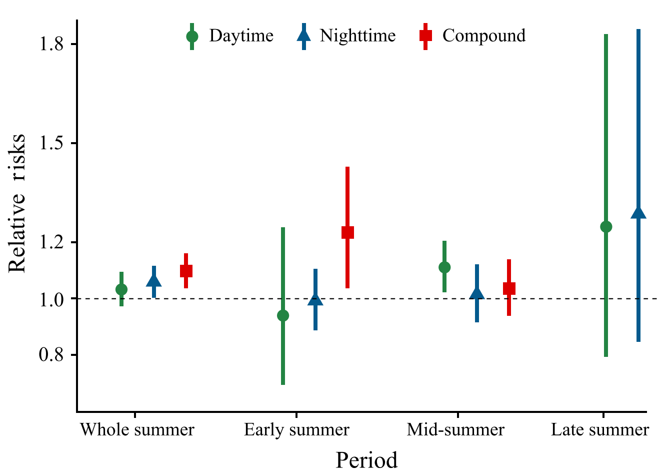

Fig. 2. Relative risks and 95% CIs of ambulance caused by hot extremes during the whole, early, middle and late summers in Shenzhen, China (No compound heat events were found in the late summer of 2015−2016).

We estimated a much larger number of heat-related ambulance dispatches under the 2 °C warming scenario compared with 1.5 °C (Table 2). Hot extremes due to the extra half-degree warming by the middle of the 21st century (2020−2059) would result in an additional 488 (16.8%) ambulance dispatches annually, and an additional 1068 (30.1%) per year by the end of the 21st century (2060−2099). Females and people aged 18−44 will be most sensitive to the further 0.5 °C warming, with a rise of 30% and 47% during 2060−2099, respectively. Specifically, the increase in ambulance dispatches due to urinary disease would rise by 52%, alcohol intoxication by 36%, and trauma by 23% during 2060−2099 under the 2 °C warming scenario.

As previously mentioned, the periods of consecutive exposures are projected to change, with more frequent occurrences in nighttime (nighttime hot extremes) and both daytime and nighttime (compound hot extremes). The projected annual numbers of heat-related ambulance dispatches with and without the consideration of cumulative heat exposure are presented in Table 3. Substantial additional impacts were associated with cumulative heat exposure, with more than 80% additional health burden caused during 2060−2099.

4. Discussion

This study presents projections of heat-related human morbidity under specific climate change scenarios consistent with the Paris Agreement. Additional health impacts due to

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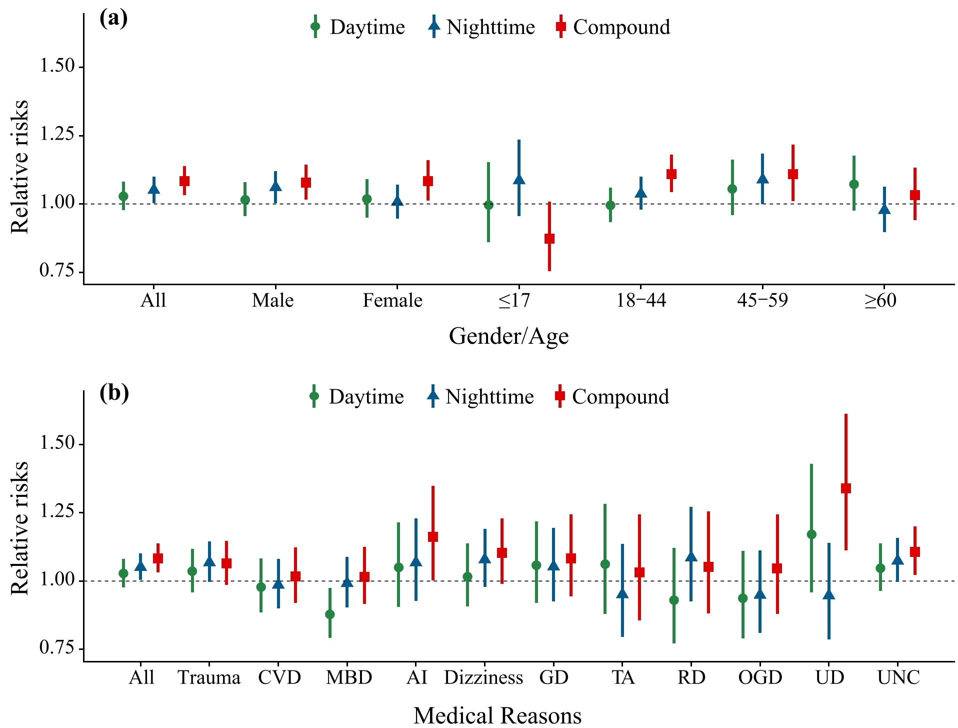

Fig. 3. Relative risks and 95% CIs of heat-related ambulance stratified by gender and age (a), and medical reasons for calling (b) (CVD, cardiovascular disease; MBD, mental and behavior disorder; AI, alcohol intoxication; GD, gastrointestinal disease; TA, traffic accident; RD, respiratory disease; OGD, obstetric or gynecological problem; UD, urinary disease; UNC, unclassifiable disease).

cumulative heat exposure within a day, and the subsequent differential health burdens under the 1.5 °C and 2 °C warming scenarios associated with consecutive exposure were also investigated. This study modeled compound daytime and nighttime hot extremes when projecting future heat-related health impacts, which allows for a more comprehensive understanding of the different impacts posed by the 1.5 °C and 2 °C warming scenarios.

Being the front line of medical services, ambulance dispatches data are particularly well suited to detect the early effects of heat stress and to reflect changes in medical and health utilization over time. As the final endpoint of an illness, mortality data only reflect a small portion of the total health burden, whilst ambulance dispatches may capture potential at-risk populations, such as those with heat exhaustion or dizziness, that may not be identified with mortality or inpatient admissions data, thus leading to many more adverse health events. In addition, recent studies suggest that heat-related mortality burdens may be reducing due to increased public health adaptation to heat, however, demands on medical services due to heat stress still remain high (He et al., 2018; Huang et al., 2015; Li et al., 2016). Thus, estimating the impact of hot extremes on ambulance services will help the allocation of health resources to meet the current and future needs.

In this study, the effects of future hot extremes due to an extra half-degree warming on ambulance dispatches were greatest for people aged 18–44 years, even though they have not been recognized as a high-risk group in previous literature (Green et al., 2019; Guo 2017; Hess et al., 2012). One possible reason is that people in this age group may be more likely than other age groups to work outdoors, increasing the likelihood of work-related injuries associated with heat exposure (Calkins et al., 2016; Ma et al., 2019; Sheng et al., 2018; Varghese et al., 2019). Thus, specific heat intervention strategies should not only target known vulnerable groups such as the elderly, but also protect young and middle-aged working populations. Another possible reason is that emergency services required by younger people are mediated by alcohol intake, which may increase during hot weather. This is further suggested by males being at higher risk at nighttime compared to females. Long-term goals for future health planning should focus on allocation of health resources and emergency services for sub-groups of the population identified in this study. Pre-disaster interventions (e.g., health education programs) should be delivered to young working adults to strengthen their self-adaptation and health risk management.

With the scope of limiting global warming well-below 2 °C, China pledges to achieve CO_2 emissions peak before 2030 and carbon neutrality before 2060. Here we showed that even in the 1.5 °C warming scenario would cause 3452 heat-related ambulance dispatches annually in Shenzhen, and that are expected to increase by about 31% (4520) due to the further warming from 1.5 °C to 2 °C during 2060s–2090s. This is because a warmer climate will not only have more frequent high temperatures, but also result in a higher proportion of nighttime heat events and compound hot extremes. We acknowledged that, in projecting future heat-related health

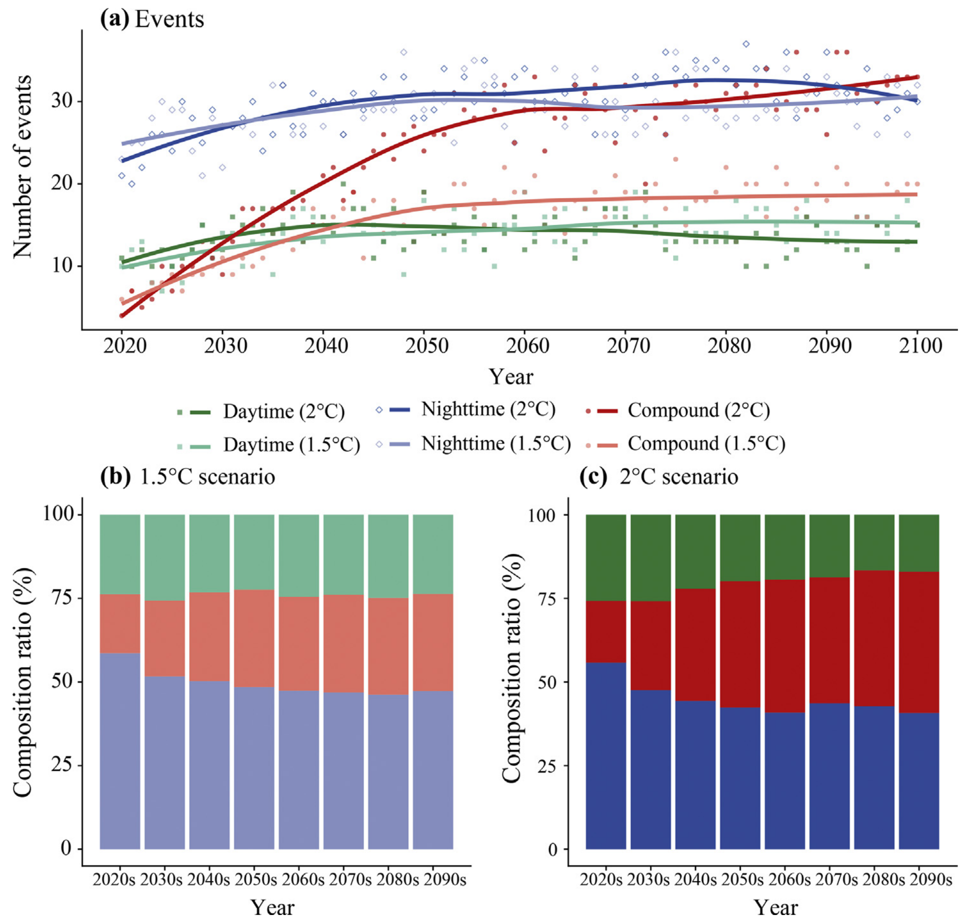

Fig. 4. Projected numbers (a) and the composition of hot extremes in 2020–2099 under the 1.5 °C (b) and 2 °C (c) scenarios.

burdens, we do not consider other factors that are likely to modify the health burdens, such as demographic changes and adaptation strategies. This is because these simplified assumptions could help to separate health impacts of global warming from the effects of other factors. Consistent with previous studies (Laaidi et al., 2012; Macintyre et al., 2018), we found higher risks during nighttime and compound events. The results therefore suggested a need for better recognition of the danger posed by nighttime heat, and also better-targeted strategies for response against consecutive heat exposure.

Urban residents are more vulnerable to hot extremes, as the amount of warming caused by climate change is intensified by urban heat island effect (UHI), which means that people who live in cities are going to face higher temperatures and stronger heat waves in the future. Nighttime temperatures in UHIs remain high. This is because buildings, sidewalks and parking lots block heat coming from the ground from rising into the cold night sky. The UHI effects can increase not only the surface temperature in summer but also the annual heat wave days, accompanied by long-lasting and intensified heat stress (Heaviside et al., 2016). Since urban residents now comprise over half of the world's population, and the citizens are particularly sensitive to the heat events, appropriate planning, such as 'cool city' initiatives, are essential for the urban heat management. For example, citywide planning related to climate change adaptation such as improvement of urban greenery and re-design of urban informal settlements (e.g., urban villages) should be applied in the locations of residences and workplaces.

Climate change may increase local demand for medical services, which may potentially alter the number of health staff and facilities required. When medical services are operating at full capacity there is a danger that the unanticipated

Table 2
Projected annual number of ambulance dispatches attributed to hot extremes during summer seasons under the 1.5 °C and 2 °C warming scenarios.

Group		Baseline	2020–2059		2060–2099	
		(2015–2016)	1.5 °C	2 °C	1.5 °C	2 °C
All		2183	2909	3397	3452	4520
Gender	Male	1084	1543	1776	1803	2349
	Female	349	466	605	604	901
Age (years)	18–44	740	1230	1522	1517	2226
	45–59	514	660	755	772	974
	≥60	115	80	109	114	139
Diagnosis	Trauma	865	1109	1246	1277	1568
	Alcohol intoxication	319	417	502	508	689
	Dizziness	256	371	427	433	565
	Gastrointestinal disease	166	197	227	233	292
	Respiratory disease	34	98	107	107	145
	Urinary disease	123	125	173	173	263

Table 3
Comparison between projected numbers of ambulance dispatches attributable to hot extremes defined by single daily maximum temperature index (single event) and by compound temperature indexes (compound event) under the 1.5 °C and 2 °C warming scenarios.

Period	Scenario	AN of single event[a]	AN of compound event[b]	Magnification times[c]
2020−2059	1.5 °C	1495	2909	1.94
	2.0 °C	1859	3397	1.83
2060−2099	1.5 °C	1906	3452	1.81
	2.0 °C	2490	4520	1.82

Notes:
[a] Project without the consideration of changes in periods of consecutive exposure due to climate change.
[b] Project with the consideration of changes in periods of consecutive exposure due to climate change.
[c] This figure represents the amplification of health impacts (ANs) associated with cumulative heat exposure in the same warming scenario and during the same period, calculated by AN of compound event/single event).

occurrence of additional hazards may leave health systems unable to cope. It remains to be seen whether the impacts of a major heat-wave in 2020 are amplified in countries already stretched dealing with COVID-19. Since heat-related illnesses and deaths are mostly preventable, emphasis should be placed on minimizing the number of people suffering heat-related illnesses, which could help to reduce the number of visits to already overstretched hospitals. In the healthcare sector, medical professionals and other first-aiders should be trained to be aware of potential heat stress cases, and should be aware of the thermal risks themselves may face while wearing personal protective equipment and working in hot environments. In addition, future health programming and operations should consider climate risks and vulnerability to increase the resilience of public climate change.

Previous studies on future heat-related health impacts are mainly based on changes in mean temperatures or the number of extreme hot days (Benmarhnia et al., 2014; Gasparrini et al., 2017; Kingsley et al., 2016; Wang et al., 2016b), but few studies considered the additional dangers of consecutive heat exposure and the likely changes in such days. As suggest in our results and also identified in previous studies (Chen et al., 2019; Mukherjee and Mishra 2018; Wang et al., 2020a), daytime- and nighttime-compound events will occur with much greater frequency in the future. With the consideration of consecutive heat exposure, here we showed substantial additional impacts on human morbidity. Moreover, without considering changes in periods of consecutive heat exposure, the projected future health impacts of climate change may be substantially underestimated in previous research. With rapid urbanization, the UHI effect may amplify the impacts of hot extremes in many cities around the world (Hu et al., 2019; Manoli et al., 2019; Murage et al., 2020; Qiu et al., 2017; Santamouris 2015). Thus, future research projecting climate change-related health burdens should evaluate the significance of consecutive heat exposure and changes in nighttime exposure, rather than merely based on mean changes in projected temperature values.

The present study has several limitations. First, to identify the types of compound events with high risks and their acute effects, the present study treated compound events as independent events, without consideration of the additional impacts of compound events that aggregated on consecutive days. Since the long-lasting compound events may cause additional effects on human health, future research that considers the health impacts of compound events that lasting for several days are needed to assess the health risks of compound events more accurately. Second, due to the availability of short-period ambulance data in Shenzhen but with large amount the daily cases, we assessed the health impacts of compound events based on ambulance dispatches data during 2015−2016. Longer sequence observations are needed to strengthen the health risks during the compound events. Third, in this study, temperature exposures were measured from a fixed-site meteorological station, which may not reflect the true levels of individual exposure. Due to the effects of UHI and the spatial variation of temperature exposure within a city, the heterogeneity of temperature should be considered in future research.

5. Conclusion

This study identifies the time-period of heat exposure with high risks, and assesses future heat-related health risks with the consideration of compound daytime and nighttime heat exposure under the 1.5 °C and 2 °C warming scenarios. Higher risks were found during consecutive daytime and nighttime heat exposure. Assuming no changes in the population and future vulnerability, we concluded that an extra half-degree warming from 1.5 °C to 2 °C would dramatically increase the heat-related health burden, with ambulance dispatches increased by 31% by 2100.

Without consideration of consecutive heat exposure may underestimate health impacts significantly, especially in the context of climate change. Thus, the inclusion of expected changes in thermal characteristics, such as more events of consecutive heat exposure, should be considered in the projections of health impacts related to climate change. Our results suggested that minimizing the warming from 2 °C to 1.5 °C target can substantially reduce the burden of disease, supporting the argument for mitigation policies designed to achieve a more stringent target in the Paris Agreement.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.accre.2021.09.001.

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